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Computer analysis of 3-phase induction motor operation on an open-delta distribution system

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COMPUTER ANALYSIS OF 3-PHASE INDUCTION MOTOR

OPERATION ON AN OPEN-DELTA

DISTRIBUTION SYSTEM

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ABSTRACT

Open-delta/open-delta and open-wye/open-delta transformer banks are often used as an economic means of supplying simultaneous single-phase and 3-phase loads. If the 3-phase load is an induction motor and if these banks are used, the inherent voltage unbalance causes increased losses and uneven heating that may lead to motor failure. Two previously published theories are used to predict motor heating that is caused by the unbalanced voltages and the motor derating that is necessary to prevent insulation failure.

ACKNOWLEDGEMENTS

I owe an especial debt of gratitude to Dr. Earl F. Richards for his suggestions and criticisms during the progress of this endeavor. His patience and guidance were major contributions for the completion of this thesis.

My thanks go also to Prof. George McPherson for his valuable advice and helpful suggestions. I am also indebted to my wife, Linda, whose patience and understanding provided the support I needed.

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I. INTRODUCTION

The growth of 3-phase loads in areas that were previously single-phase has prompted the utilities to seek a satisfactory method of installing the 3-phase service. Although a separate 3-phase system could be built, a method that is economically attractive to the utilities is to supply both single-phase and 3-phase loads from the same transformer bank. Often the old system can be expanded to 3-phase service by simply adding a second transformer to form either an open-delta/open-delta or open-wye/open-delta transformer bank.

Both leading and lagging open-delta connections are used. They are defined as follows:

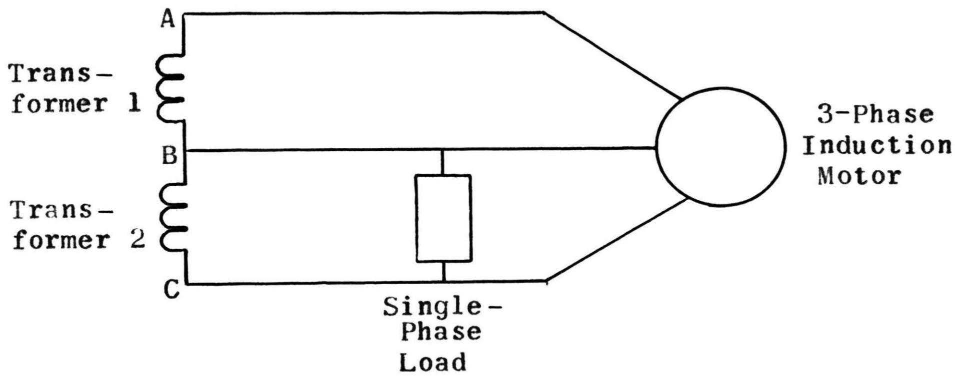
1. In the open-delta leading connection, the voltages across the transformer supplying the single-phase load leads the voltage across the other transformer by 120 degrees.

2. In the open-delta lagging connection, the voltage across the transformer supplying the single-phase load lags the voltage across the other transformer by 120 degrees.

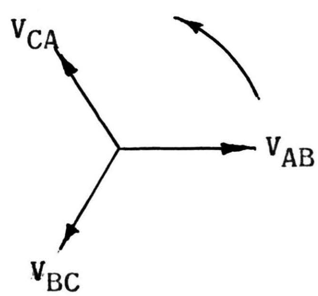
The circuit and vector diagrams of Fig. 1 describe both connections.

Unfortunately, the secondary voltages of the open-delta systems are subject to voltage unbalance caused by unequal loading and unequal transformer impedances. Section 14.34 of NEMA Standard MG1-1972 defines this unbalance as

$$\begin{array}{l}\text{Percent}\\ \text{Voltage}\\ \text{Unbalance}\end{array} = 100 \times \frac{\text{Maximum deviation from average voltage}}{\text{Average voltage}} .$$



(a)



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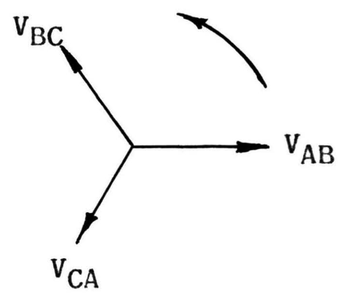


(c)

Fig. 1. Open-Delta Distribution System. (a) Wiring Diagram; (b) Phase Sequence for Open-Delta Lagging Connection; (c) Phase Sequence for Open-Delta Leading Connection.

The voltage unbalance is usually small; however, it can become quite serious when the 3-phase load is an induction motor. Excessive motor heating caused by the unbalanced conditions may eventually lead to insulation failure. The amount of voltage unbalance which a motor can constantly withstand without damage varies with induction motor design. Winding insulation, winding pitch, type of rotor, and ventilation details may all affect the maximum winding temperature. To prevent insulation failure, the motor load should be derated until the maximum winding temperature does not exceed that of rated conditions. Present methods of calculating the exact amount of derating are cumbersome.

The purpose of this paper is to develop a computer program capable of analyzing an open-delta distribution system, predicting motor heating, and determining the amount of derating necessary to prevent motor failure. The necessary background analysis of the open-delta system and the methods used to predict winding temperatures and to derate motor loads are presented. Laboratory testing was performed to verify the modeling procedure, analysis, and digital program.

II. REVIEW OF LITERATURE

The open-delta distribution system, which serves a single-phase load and 3-phase induction motor, was analyzed by Anderson and Ruete[2] and Bankus and Gerngross[3] in papers written in 1954. The voltage unbalance on open delta systems was discussed in both papers. Anderson and Ruete derived general equations which could be used to calculate voltage unbalance. Bankus and Gerngross recommended transformer sizing that would result in a low voltage unbalance and in maximum utilization of transformer KVA. In a later paper, Bankus and Gerngross[4] compared the advantages and disadvantages of using either the open-delta leading or open-delta lagging transformer connections.

Williams[11] analyzed the effects of voltage unbalance on motor operation and concluded that the unbalanced voltages cause increased motor losses and uneven heating. In another paper, Gafford et al. 8 attributed the rise in motor temperature under unbalanced conditions to increased copper losses and unbalanced spatial distribution of stator heating.

More recently, investigations have been made on the spatial distribution within the motor of heat resulting from unbalanced voltages, and methods of derating motor loads to prevent insulation failure have been proposed. The two extremes for determining the amount of derating necessary are presented in papers by Lee[6] and Berndt and Schmitz[5]. Lee assumed that the thermal impedance between stator windings was negligible; therefore, any additional heating caused by unbalanced voltages is evenly distributed among all three windings. To prevent insulation failure, the motor load should be derated until the total losses in the stator windings do not exceed the losses under rated conditions. On the other hand, Berndt and Schmitz assumed that the thermal impedance between windings is infinite. According to their theory, the motor load should be derated until the maximum current in any phase is equal to or less than rated current. Whereas Lee presented an optimistic derating of the motor load, Berndt and Schmitz were overly pessimistic. Later, Rao and Rao[9] presented two additional methods of motor derating by taking into account details of the winding and insulation. Because the methods of motor derating presented by Lee and Berndt and Schmitz require a minimum knowledge of motor construction, they shall be considered in this paper.

III. DERIVATION OF THE COMPUTER MODEL

Determining the exact amount of motor derating requires an accurate analysis of the open-delta system. The unbalanced voltages must be calculated and their effects on motor operation determined. The unbalanced conditions make these calculations laborious. A generalized computer program, which is capable of analyzing the open-delta system, predicting motor heating, and determining necessary derating, would be timesaving. Such a program has been written and is in the files of the Power Section of the Electrical Engineering Department at the University of Missouri-Rolla[10]. The derivation of the system equations and the analysis of motor heating which are used in the program are presented below.

A. System Equations

An equivalent circuit of an open-delta system that includes transformer secondaries, service leads and cables, single-phase load, and 3-phase induction motor is shown in Fig. 2. By writing Kirchoff's voltage equations for the circuit, the voltages at the motor terminals can be expressed as

$$\begin{vmatrix} v_{ab} \\ v_{bc} \end{vmatrix} = \begin{vmatrix} (Z_1+2Z_L+2Z_C) & Z_C & Z_L \\ Z_C & (Z_\ell+2Z_C) & Z_\ell \end{vmatrix} \begin{vmatrix} I_1 \\ I_2 \\ I_3 \end{vmatrix} + \begin{vmatrix} V_{AB} \\ 0 \end{vmatrix} . \qquad (1)$$

For simplicity, Eq. (1) can be written

$$\overline{V}_t = [Z]\overline{I} + \overline{V}. \qquad (2)$$

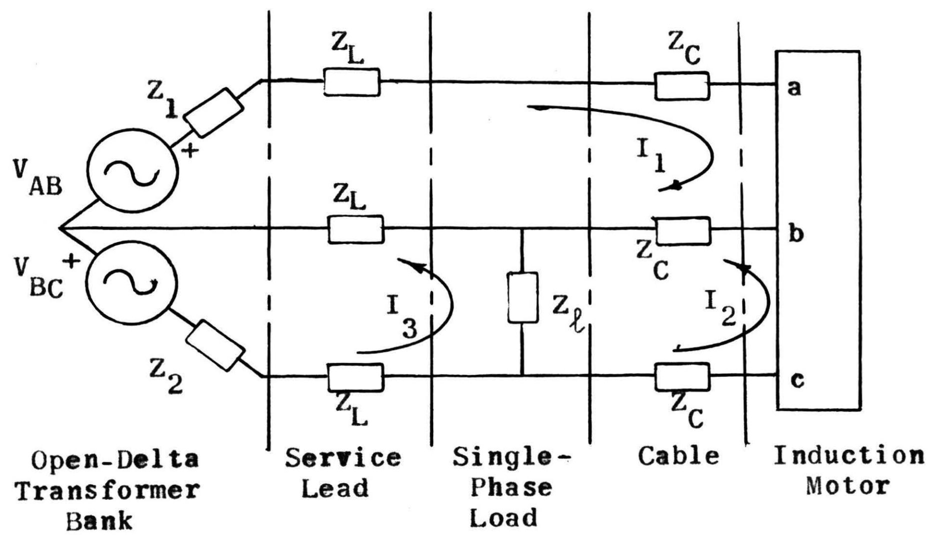


Fig. 2. Model of Open-Delta Distribution System.

The stator of the induction motor is assumed to be delta-connected. Each phase of the motor can be modeled by its positive and negative sequence circuits shown in Fig. 3 and Fig. 4.[8] The zero sequence circuit need not be considered because the delta connection is assumed. The total positive sequence impedance, Z^+, and negative sequence impedance, Z^-, can be derived from Fig. 3 and Fig. 4 to be

$$Z^+ = \frac{z[R_s + R_r^+/s + j(X_s+X_r^+)]}{z + R_s + R_r^+/s + j(X_s+X_r^+)} \tag{3}$$

in which

$$z = \frac{jR_iX_m}{(R_i+jX_m)}$$

and

$$Z^- = R_s + \frac{R_r^-}{(2-s)} + j(X_s+X_r^-) \tag{4}$$

From Fig. 5, the positive and negative sequence voltages at the motor terminals are

$$\begin{vmatrix} v_{ab}^+ \\ v_{ab}^- \end{vmatrix} = \begin{vmatrix} Z^+ & 0 \\ 0 & Z^- \end{vmatrix} \begin{vmatrix} I^+ \\ I^- \end{vmatrix} \tag{5}$$

or

$$\overline{V}_s = [Z_s]\overline{I}_s . \tag{6}$$

The phase sequence is assumed to be v_{ab}, v_{bc}, v_{ca}. The symmetrical components transformation can be applied to the voltages at the motor

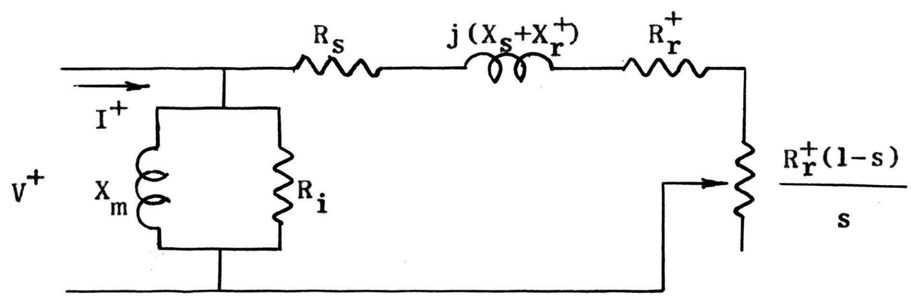


Fig. 3. Positive Sequence Model of One Phase of the Induction Motor.

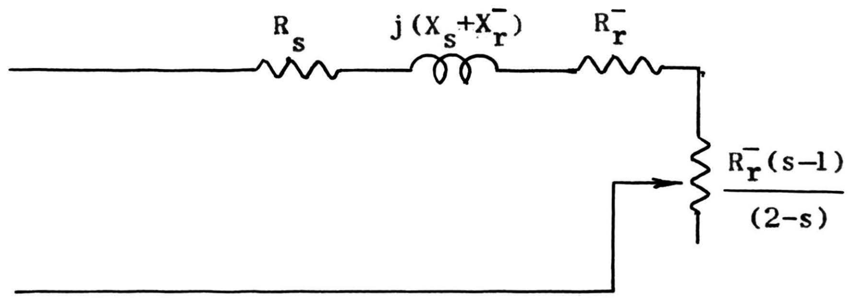


Fig. 4. Negative Sequence Model of One Phase of the Induction Motor.

terminals to obtain

$$\begin{vmatrix} v_{ab}^{+} \\ v_{ab}^{-} \\ v_{ab}^{o} \end{vmatrix} = \frac{1}{3}\begin{vmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{vmatrix}\begin{vmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{vmatrix} \tag{7}$$

in which

$$a = 1\angle 120^{0} .$$

Because the zero sequence impedance is infinite, the zero sequence voltage is zero. The terminal voltage v_{ca} can be eliminated from Eq. (7) to yield

$$\begin{vmatrix} v_{ab}^{+} \\ v_{ab}^{-} \end{vmatrix} = \begin{vmatrix} (1-a^2)/3 & (a-a^2)/3 \\ (1-a)/3 & (a^2-a)/3 \end{vmatrix}\begin{vmatrix} v_{ab} \\ v_{bc} \end{vmatrix} . \tag{8}$$

Eq. (8) can be rewritten as

$$\overline{V}_s = [A]\overline{V}_t . \tag{9}$$

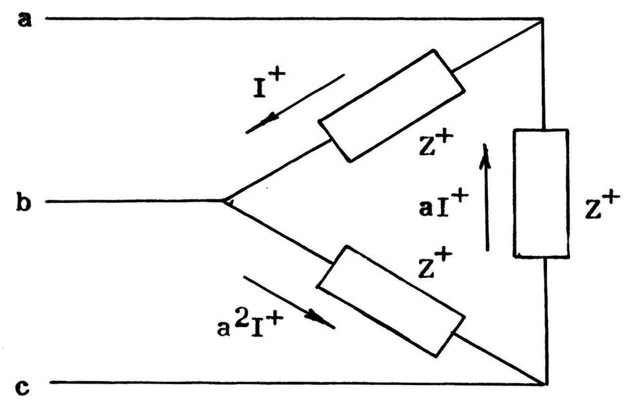
The substitution of Eqs. (2) and (6) for $\overline{V}_t$ and $\overline{V}_s$ in Eq. (9) gives

$$[Z_s]\overline{I}_s = [A][Z]\overline{I} + [A]\overline{V}. \tag{10}$$

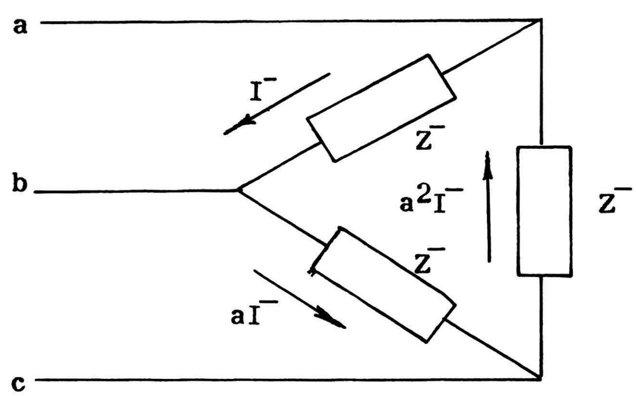
The application of Kirchoff's current law to the circuits in Fig. 5 and the summation of both positive and negative sequence components of the line currents I_1 and I_2 (see Fig. 1) result in the following two equations:

$$I_1 = (1-a)I^{+} + (1-a^2)I^{-} \tag{11}$$

and



(a)



(b)

Fig. 5. Three-Phase Sequence Models of an Induction Motor. (a) Positive Sequence Model; (b) Negative Sequence Model.

$$I_2 = (a-a^2)I^+ + (a^2-a)I^- . \tag{12}$$

A third equation is obtained by applying Kirchoff's voltage law to loop 3 (see Fig. 2). The substitutions of Eqs. (11) and (12) for I_1 and I_2 in this equation and a rearrangement of the terms results in

$$I_3 = \frac{-Z_L(1-a) + Z_\ell(a-a^2)}{(Z_2+2Z_L+Z_\ell)} I^+ + \frac{-Z_L(1-a^2) + Z_\ell(a^2-a)}{(Z_2+2Z_L+Z_\ell)} I^- - \frac{V_{BC}}{(Z_2+2Z_L+Z_\ell)} \tag{13}$$

In matrix form, these three current equations are

$$\begin{vmatrix} I_1 \\ I_2 \\ I_3 \end{vmatrix} = \begin{vmatrix} (1-a) & (1-a^2) \\ (a-a^2) & (a^2-a) \\ \dfrac{-Z_L(1-a)+Z_\ell(a-a^2)}{(Z_2+2Z_L+Z_\ell)} & \dfrac{-Z_L(1-a^2)+Z_\ell(a^2-a)}{(Z_2+2Z_L+Z_\ell)} \end{vmatrix} \begin{vmatrix} I^+ \\ I^- \end{vmatrix} + \begin{vmatrix} 0 \\ 0 \\ \dfrac{-V_{BC}}{(Z_2+2Z_L+Z_\ell)} \end{vmatrix} \tag{14}$$

or

$$\overline{I} = [W]\overline{I}_s + \overline{I}_{t2} . \tag{15}$$

By inserting Eq. (15) into Eq. (10) and solving for the currents in the motor sequence models, $\overline{I}_s$, one obtains

$$\overline{I}_s = ([Z_s] - [A][Z][W])^{-1}([A][Z]\overline{I}_{t2} + [A]\overline{V}) . \tag{16}$$

With a knowledge of the input voltages and circuit elements, Eq. (16) can be solved for the currents in the motor sequence models. The line currents at the motor terminals can then be calculated from Eq. (15). The sequence voltages at the motor terminals, $\overline{V}_s$, are determined by inserting the values of $\overline{I}_s$ into Eq. (5). The line to line terminal voltages are then calculated by rearranging Eq. (9) to obtain

$$\overline{V}_t = [A]^{-1}\overline{V}_s. \tag{17}$$

Knowledge of the voltages and currents in the motor sequence models permits the calculation of the motor losses.

B. Motor Losses

The prediction of the spatial distribution of heat in an induction motor is a formidable problem. The wide variety of induction motors make any general analysis difficult by requiring intricate details of motor construction.

To keep the computer program in this study as general as possible and to limit to a minimum the amount of required knowledge of motor construction, the two methods of derating presented by Lee[6] and Berndt and Schmitz[5] are considered. Neither method can predict the exact amount of derating necessary, but they do determine the bounds which should be considered. These restrictions and considerations, along with experience and engineering judgment, can then be employed to determine proper derating.

Unbalanced voltages cause an increase in rotor copper loss.[8,10] This loss can be calculated by adding the powers dissipated in R_r^+ and R_r^- for all three phases. (See Figs 3 and 4.) In some cases, such as machines having deep bar or double cage rotors, this loss can become significant in determining the critical temperature.[5,8,10] Both derating methods presented by Lee and Berndt and Schmitz assume that the rotor copper loss has a negligible effect on motor operation.

In many motors, the stator copper loss is the determining factor for derating the motor load.[5,6,9] The losses in R_s (the resistance of each of the stator windings) can be calculated from circuit theory. (See Figs. 3 and 4.) As a result of the unbalanced line currents, these losses are not equal in each winding. It is here that the two theories presented by Lee and by Berndt and Schmitz differ. Lee assumed that the thermal impedance between stator windings is negligible; therefore, the temperatures of all three phases are equal and proportional to the average of the powers dissipated in the stator windings. On the other hand, Berndt and Schmitz assumed that the thermal impedance is infinite and that overheating will result in the phase dissipating the most power. Neither of the theories is completely correct. The actual critical temperature lies between the two estimates.

Past evidence has shown that for approximately each 10^{o}C rise in winding temperature, the insulation life is roughly halved.[1] To estimate the effects of the unbalanced voltages on motor life, the temperature rise in the motor is calculated. The rise in winding temperature, ΔT, above ambient is assumed to be directly proportional to the power dissipated in the winding. The proportionality constant, k, is calculated by dividing the designed stator temperature rise, $\Delta T_{designed}$, above an assumed 40^{o}C ambient temperature by the power dissipated per phase in the stator under balanced rated conditions, or

$$\Delta T = kI_s^2R_s \tag{18}$$

in which

$$I_s = \text{Total Current in } R_s \text{ (See Figs. 3 and 4.)} \tag{19}$$

and

$$k = \frac{\Delta T_{designed}}{I_{s_{rated}}^2 \; R_s}. \qquad (20)$$

To protect the motor, the maximum winding temperature should not be allowed to exceed the temperature under balanced rated conditions. The motor load should be derated until the stator temperature is within safe limits. Bounds on the amount of derating necessary can be obtained from the two theories presented above.

Refinements of these two methods to include rotor heating, type of winding insulation, and winding pitch could be made to obtain better accuracy. Although the derivation of the program presented in this paper is derived for two specific methods of derating, minor changes can make it applicable to any other derating theory.

C. Implementation of System Equations and Motor Heating in a Computer Model

By using the system equations and derating methods discussed above, a computer program has been written. The program determines the unbalanced voltages on an open-delta system, predicts motor heating, and determines load derating limits. To make the program easier to use and more generalized, the modifications which follow are included in the program.

The impedance of the single-phase load is required to solve Eq. (16). Usually, the data given for the single-phase load are the total power, KVA, and the power factor, pf. As a result of the voltage unbalance, the voltage across the single-phase load is not explicitly known prior to the analysis; therefore, the exact value of Z_ℓ cannot be calculated before solving Eq. (16). An iteration technique is used to adjust the impedance of Z_ℓ until the desired single-phase load is obtained. The initial guess of Z_ℓ is calculated by assuming that the voltage across the single-phase load, V_ℓ, is V_{AB}. Each subsequent guess is made by solving Eq. (16), determining a new value of V_ℓ, and recalculating a new guess of the single-phase load, Z_ℓ^{k+1}, by

$$\left|Z_\ell^{k+1}\right| = \frac{(V_\ell^k)^2}{KVA} \tag{21}$$

and

$$Z_\ell^{k+1} = \left|Z_\ell^{k+1}\right| (pf) + j\left| Z_\ell^{k+1}\right| (1-pf^2)^{1/2} \tag{22}$$

in which $\left|Z_\ell^{k+1}\right|$ is the magnitude of the $k^{th}+1$ guess of Z_ℓ. The iteration loop is executed until the single-phase load is within a specified tolerance of the KVA and power factor desired.

In addition to knowing the impedance of the single-phase load, Eq. (16) also requires that the slip of the induction motor be specified. This is impractical because the programmer may not always know the value of slip when the motor is operated at other than the rated load or under unbalanced conditions. A more reasonable quantity to specify is the output horsepower of the motor. To achieve this, a second iteration loop is included in the program. Eq. (16) is originally solved by using the value of slip the motor would have operating at nameplate speed. The power output of the motor, P, is then determined by summing the power outputs of the motor sequence models to give

$$P = 3\left|I_r^+\right|^2 R \left(\frac{1-s}{s}\right) + 3\left|I_r^-\right|^2 R^- \left(\frac{s-1}{2-s}\right) \tag{23}$$

in which $|I_r^+|$ and $|I_r^-|$ are the magnitudes of the currents in the rotor resistances R_r^+ and R_r^- respectively. (See Figs. 3 and 4.) This power is compared with the desired output power of the motor. If the error exceeds a specified tolerance, the slip is adjusted in a direction to minimize the error. The error criterion used is

$$E = 746(hp) - P \tag{24}$$

in which hp is the desired horsepower of the motor. The new guess of slip, s^{k+1}, can be determined by

$$s^{k+1} = s^k - E/(\partial E/\partial s) \tag{25}$$

in which

$$\frac{\partial E}{\partial s} = 3|I_r^+|^2 R_r^+ \left[\frac{1}{s} - \frac{(1-s)}{s^2} \right] + 3|I_r^-|^2 R_r^- \left[\frac{1}{(2-s)} - \frac{(s-1)}{(2-s)^2} \right]. \tag{26}$$

The iterations are continued until the power output calculated in the program is within a specified tolerance of the horsepower desired.

The program should be capable of analyzing both open-delta leading and lagging connections. The difference between the two is the phase sequence of the voltages at the transformer terminals as shown in Fig. 1. The system equations derived in Section III.A assume a phase sequence of V_{AB}, V_{BC}, V_{CA}; therefore, the system is a lagging open-delta connection. To analyze a leading connection, the phase sequence must be changed to V_{AB}, V_{CA}, V_{BC}. This will result in changing Eqs. (7) and (8). These two equations will retain their same form; however,

$$a = 1\angle 240^\circ .$$

A program written for a lagging connection can also be used to analyze a leading connection by simply changing the value of a.

After these modifications, Eq. (16) can be solved for both leading and lagging connections and for specific single-phase and 3-phase loads. The unbalanced conditions can then be determined, and the power dissipated in each stator winding can be calculated. By using the analysis presented in Section III.B, the effects of the unbalanced voltages on motor operation can be estimated.

To obtain the derated value of motor load, hp_d, a third iteration loop is required in the program. The horsepower is adjusted until the critical stator power predicted by either of the derating methods is equal to the power dissipated per phase in the stator under balanced rated conditions, i.e.,

$$P_{crit} = P_{rated}. \tag{27}$$

The initial guess of the derated horsepower, hp_d^0, is the rated horsepower of the motor. The new estimate of the derated motor load, hp_d^{k+1}, is determined each time from the following expression:

$$hp_d^{k+1} = hp_d^k - hp_d^k \frac{(P_{crit} - P_{rated})}{(P_{crit} + P_{rated})} \tag{28}$$

in which

$$P_{rated} = R_s (I_{s_{rated}})^2 \tag{29}$$

$I_{s_{rated}}$ is the magnitude of the current in R_s under balanced rated conditions and is determined from the positive sequence model. (See Fig. 3.) When the predicted critical stator power is within a specified tolerance of the stator heating under rated conditions, an exit from the iteration loop occurs. This iteration loop is executed twice to obtain values for both derating methods presented in Section III.B.

The above derating procedures assume that the service factor of the induction motor is unity. For motors having service factors other than unity, derating limits can be approximated by determining the values of the derated load from the above procedure and then multiplying these values by the service factor. A flow chart of the program is shown in Fig. 6.

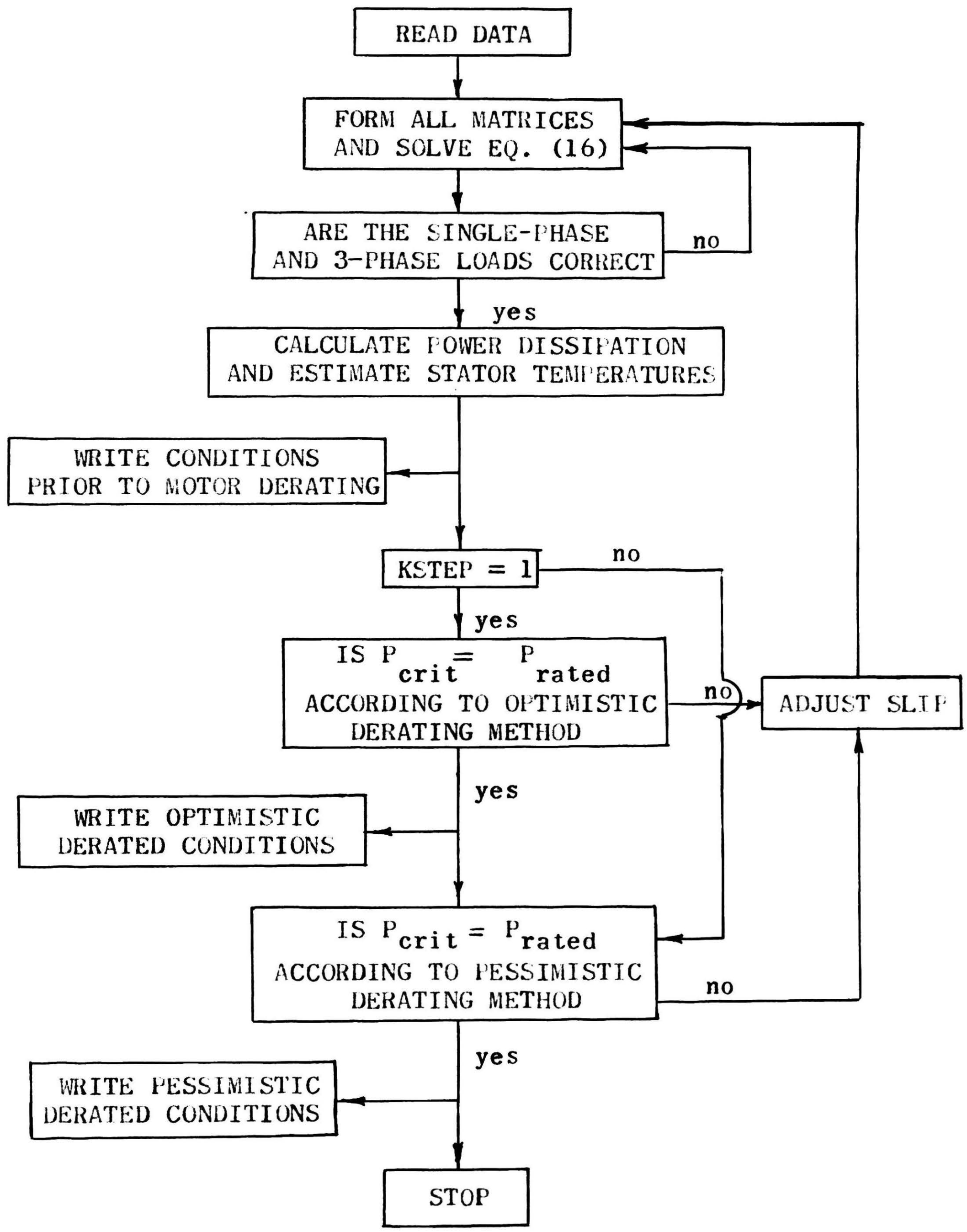


Fig. 6. Flow Chart for Computer Analysis.

IV. VERIFICATION OF THE SYSTEM MODEL

An open-delta distribution system was simulated in the laboratory. Two 5-KVA transformers were used in a lagging open-delta transformer bank to supply both a single-phase load and 3-phase induction motor.

The 3-phase motor load was a 220 volt, 4 pole, 60 hz, 3 hp induction motor having a wye-connected stator and was of deep bar squirrel cage rotor construction. The elements in the sequence models of the motor (Figs. 3 and 4) were determined to be

$$R_s = 0.850 \text{ ohm per phase}$$

$$R_i = 227. \text{ ohms per phase}$$

$$R_r^+ = 0.390 \text{ ohm per phase}$$

$$R_r^- = 0.780 \text{ ohm per phase}$$

$$X_m = 27.1 \text{ ohms per phase}$$

$$X_s + X_r^+ = 2.54 \text{ ohms per phase}$$

$$X_s + X_r^- = 2.36 \text{ ohms per phase}$$

The impedance of the lines was negligible; therefore, a 1.35 ohm resistor was added in series with transformer 2 (Fig. 1) to obtain sizable voltage unbalances for reasonable values of single-phase loads.

With a motor load of 1.5 horsepower, the unity power factor single-phase load was varied between 0 and 4 KVA. The resulting unbalanced conditions were recorded for several values of single-phase loads in this range. The same system was then analyzed in the computer program and the results were compared and are shown in Figs. 7 through 9. The voltage unbalance in Fig. 9 was calculated using the definition of voltage unbalance given in Section 14.34 of NEMA Standard MG1-1972.

Assuming that the motor was rated at 1.5 horsepower instead of 3 horsepower, the motor load was derated to keep the critical winding temperature equal to the winding temperature when the motor is operated under balanced conditions at 1.5 horsepower. Derating limits were predicted by the computer program for several values of single-phase loads and are shown in Fig. 10.

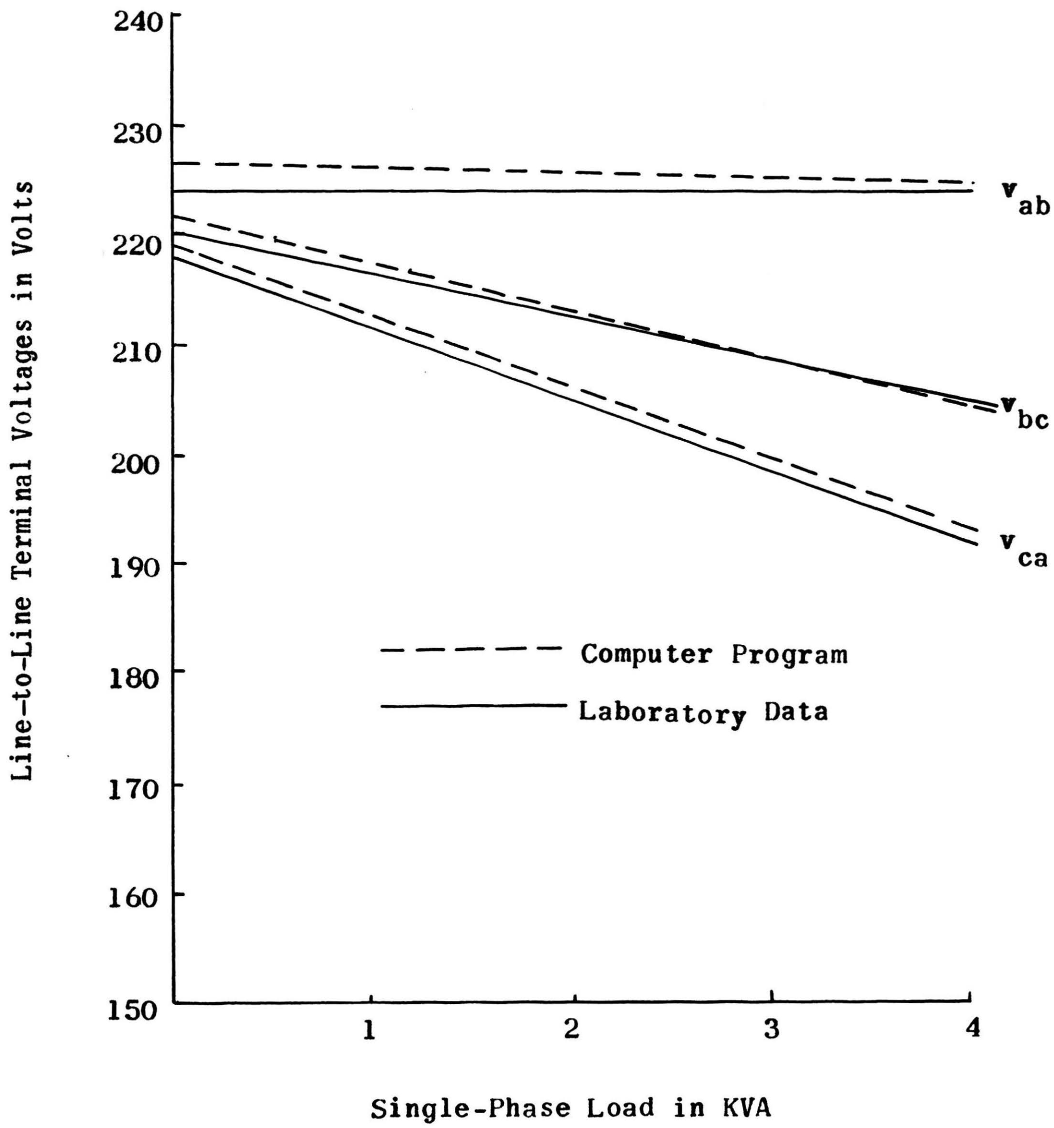


Fig. 7. Comparison of Measured and Predicted Terminal Voltages Versus Single-Phase KVA.

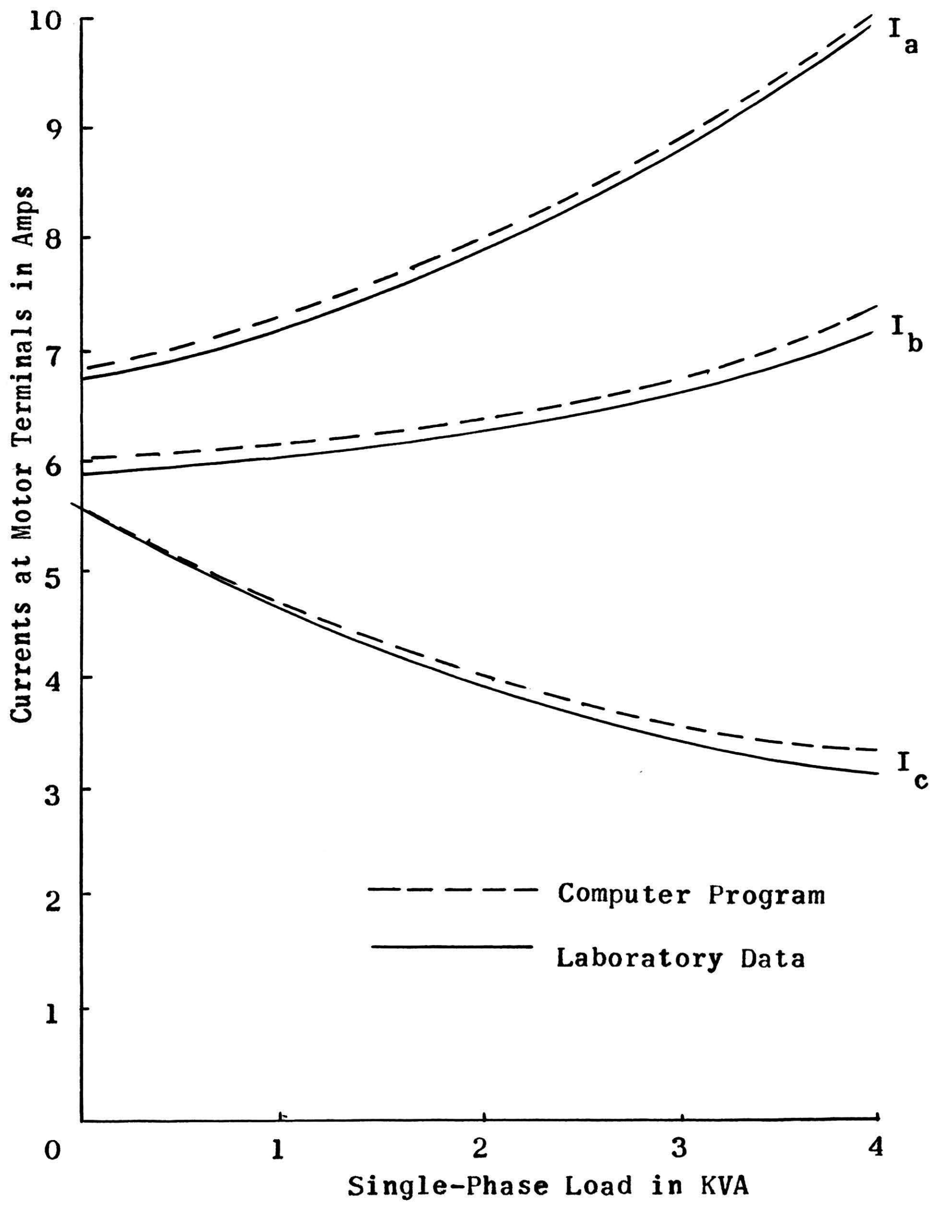


Fig. 8. Comparison of Measured and Predicted Currents at the Motor Terminals Versus Single-Phase Load.

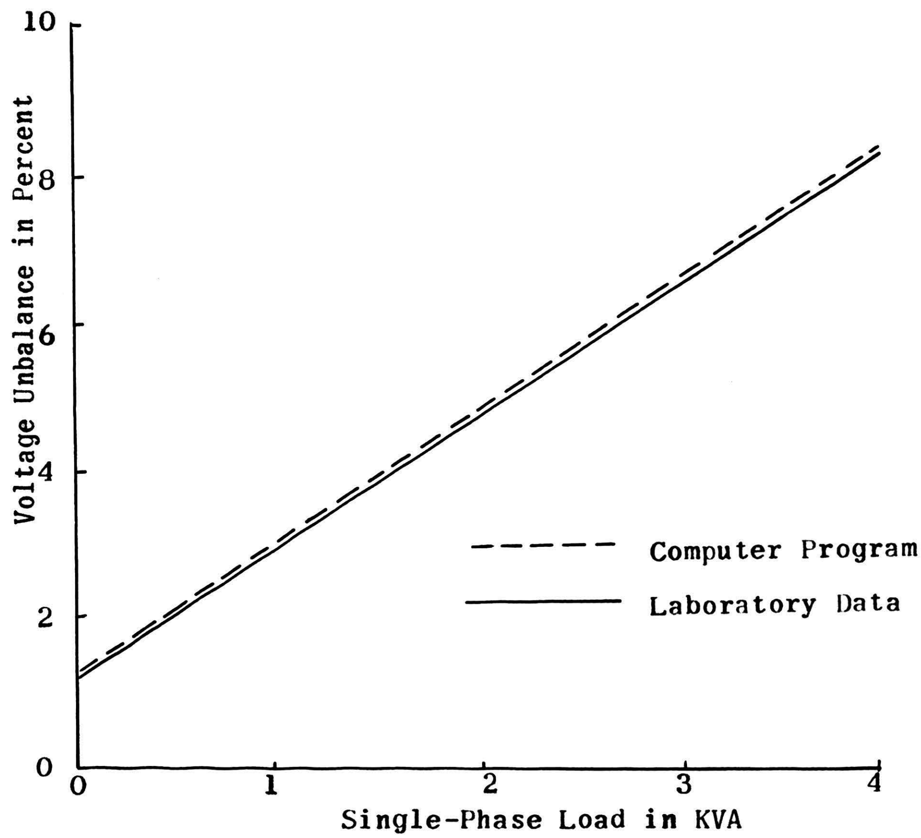


Fig. 9. Comparison of Measured and Predicted NEMA Voltage Unbalance at Motor Terminals Versus Single-Phase KVA.

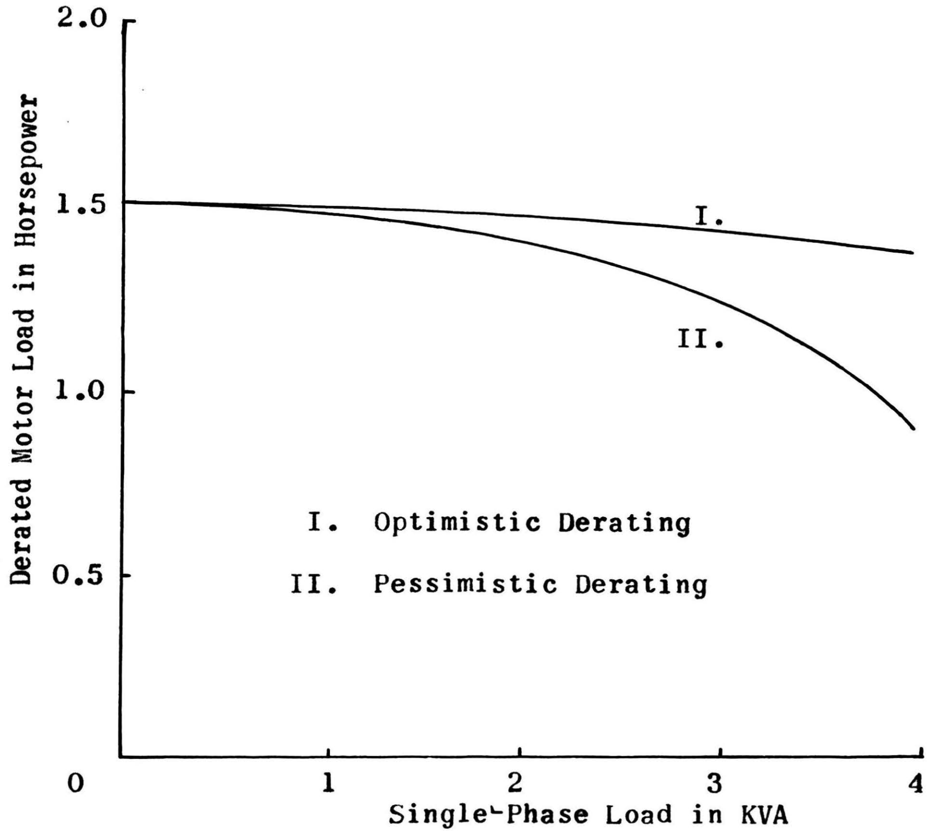


Fig. 10. Motor Derating Limits Versus Single-Phase Load for Test Motor Assuming Rated Load of 1.5 Horsepower.

V. EXAMPLE OF AN APPLICATION OF THE COMPUTER PROGRAM

A theoretical system was analyzed in a computer program with the analysis presented in this paper. The system consisted of a leading open-delta transformer bank serving a single-phase load and 3-phase induction motor. Transformer ratings were assumed to be 5 and 37.5 KVA respectively. The single-phase load was assumed to be 20 KVA at 0.9 power factor and supplied by the larger of the two transformers. The 3-phase induction motor was a 10 hp, 240 volt, 4 pole, 60 hz motor having class B winding insulation. Motor constants were assumed to be

$$R_s = 0.153 \text{ ohm per phase}$$
$$R_r^+ = 0.188 \text{ ohm per phase}$$
$$R_r^- = 0.507 \text{ ohm per phase}$$
$$X_m = 14.3 \text{ ohms per phase}$$
$$X_s+X_r^+ = 1.26 \text{ ohms per phase}$$
$$X_s+X_r^- = 0.982 \text{ ohm per phase}$$

Service leads and cables were each assumed to be 200 feet of number 2 AWG copper wire.

Without derating the motor load, the computer program predicted that the following conditions would occur:

Voltage unbalance:	1.7 Percent
Maximum stator heating (optimistic):	60 Watts
Estimated temperature (optimistic):	124 ^{o}C
Maximum stator heating (pessimistic):	72 Watts
Estimated temperature (pessimistic):	142 ^{o}C

Under balanced rated conditions, the power dissipated as heat in each of the stator windings is 57 watts at 120°C.

According to the derating method presented by Lee[6], the motor load should be derated to 9.7 horsepower. This would reduce the average power dissipation per phase in the stator windings to 57 watts. The derating method presented by Berndt and Schmitz[5] would derate the motor load to 8.9 horsepower and reduce the maximum power dissipated in any of the stator windings to 57 watts.

For this theoretical system, the effects of the unbalanced voltages on motor operation have been determined. To prevent insulation failure, the motor load should be derated to a value between 9.7 and 8.9 horsepower.

VI. RESULTS AND CONCLUSIONS

This paper has presented the background necessary to analyze an open-delta distribution system, predict motor heating, and determine derating limits. Suggestions have been made to combine the analysis of the open-delta system and the motor into one computer program. The computer program can then be used to estimate the effects of the voltage unbalance on motor operation and to determine the amount of derating necessary.

The two methods of motor derating presented in this paper can only give limits on the amount of derating necessary to protect the motor. Future research should concentrate on obtaining better thermal models which can be used to predict necessary derating.

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